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PERFORATION LIMITS FOR NONSHATTERING PROJECTILE AGAINST
THICK HOMOGENEOUS ARMOR AT NORMAL INCIDENCE

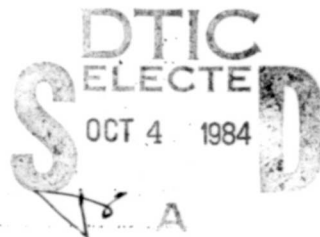
by

C. W. Curtis and R. L. Kramer

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Preface

The work described in this report is pertinent to the projects designated by the War Department as OD-75, "Investigation of the Penetration of Homogeneous and Face-Hardened Armor at Striking Velocities of 3000 ft/sec and Above," and by the Navy Department as NO-11, "Structural Defense, Testing Facilities."

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PERFORATION LIMITS FOR NONSHATTERING PROJECTILE AGAINST
THICK HOMOGENEOUS ARMOR AT NORMAL INCIDENCE

Abstract

Usingunjacketed caliber .244 projectiles that did not shatter, limit energies have been determined at normal incidence for homogeneous armor (BHN 255) ranging in thickness from $\frac{1}{4}$ to 6 calibers. For plates over 1.5 calibers thick, the data have been correlated by means of an empirical equation of the form

$$\frac{WV^2}{d^3} = R\left(\frac{e}{d}\right)^n,$$

where W is the weight of the projectile, V is limit velocity; R is a measure of the "strength" of the plate material and has units of force per unit area, e is the plate thickness, d is the diameter of the projectile, and n is a constant. With a particular projectile and plate of a given hardness, R and n are constant, but they vary with changes in the plate and projectile parameters.

- (i) R and n are independent of the mass of the projectile only for thick plate (> 1.5 calibers). For thinner plate the limit energy was found to increase with increase in mass.
- (ii) For projectiles of conventional nose shape n has a nominal value near 1.25 (less than the value usually used in De Marre formula). Changes in shape produce slight variations in both R and n . As the nose becomes sharper R and n decrease.
- (iii) There is an indication that a "scale effect" causes a small decrease in R with an increase in the caliber of the projectile.
- (iv) As expected, R increased with an increase in plate hardness.

1. Introduction

Immediately following the initiation, some three years ago, of a program to investigate the terminal-ballistic performance of hypervelocity projectiles, the Princeton University Station carried out measurements to determine perforation limits for essentially nondeforming projectiles against very thick homogeneous armor. These measurements covered plate thicknesses from $\frac{1}{4}$ to 6 calibers, but were restricted to normal attack. Performance at oblique

incidence, where the limits are often greatly affected by projectile deformations, was studied in other tests which have since been reported.

About two years ago these results at normal incidence were discussed in a contractor's informal memorandum,^{1/} but they have never been published in a form that would receive wide distribution. Despite the time that has elapsed since these experiments were carried out, the authors know of no subsequent data for unjacketed, uncapped projectiles that cover as great a range in plate thickness. The results contained in the foregoing memorandum are therefore reproduced in the present report. Unfortunately time does not permit a lengthy discussion of the experimental details.

2. Perforation limit measurements

Using a double ballistic pendulum^{2/} and the method of residual velocities,^{3/} perforation limits (Navy) were determined for caliber .244 projectiles against homogeneous armor at normal incidence. All plates in the series had the same chemical composition and heat treatment and different plates varied in hardness by not over 20 Brinell numbers. The nominal hardness of the set^{4/} was BHN 255. To provide smooth parallel faces, to permit an accurate measurement of the thickness and to furnish a good surface for making Brinell hardness readings, each plate was wet-surface ground before firing.

Both steel and tungsten carbide projectiles were used. With the high striking velocities employed (up to 4000 ft/sec for the steel and 3650 ft/sec for the tungsten carbide) neither type remained entirely undeformed in all cases; the steel projectile sometimes suffered plastic deformation resulting in a slight bulge at the bourrelet and body failures usually occurred with the

1/ Princeton Technical Memorandum No. 11.

2/ A double pendulum for use in studies of the ballistic behavior of armor, by G. T. Reynolds and R. L. Kramer, NDRC Report A-52 (OSRD-686).

3/ The ballistic properties of mild steel, including preliminary tests on armor steel and dural, by Ballistic Research Group, Princeton University, NDRC Report A-111 (OSRD-1027).

4/ Corrections of 0.2 percent in the limit energy were made for each Brinell number above or below 255.

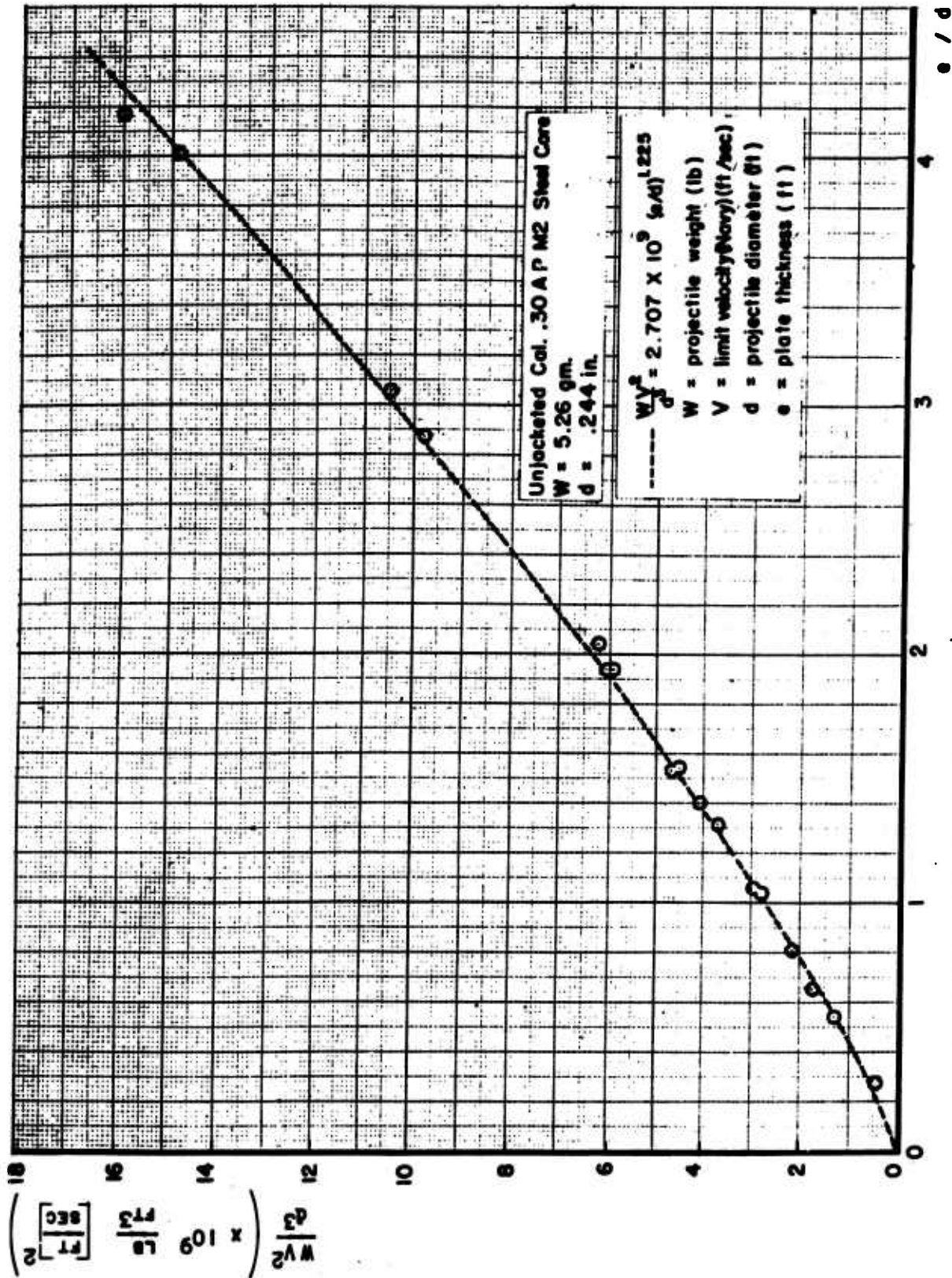


FIG. 1. SPECIFIC LIMIT ENERGY VERSUS THE RATIO OF PLATE THICKNESS e/d TO PROJECTILE DIAMETER d FOR UNJACKETED CALIBER .30 AP M2 STEEL CORES TESTED AGAINST HOMOGENEOUS ARMOR (BHN 255) AT 0° OBLIQUITY.

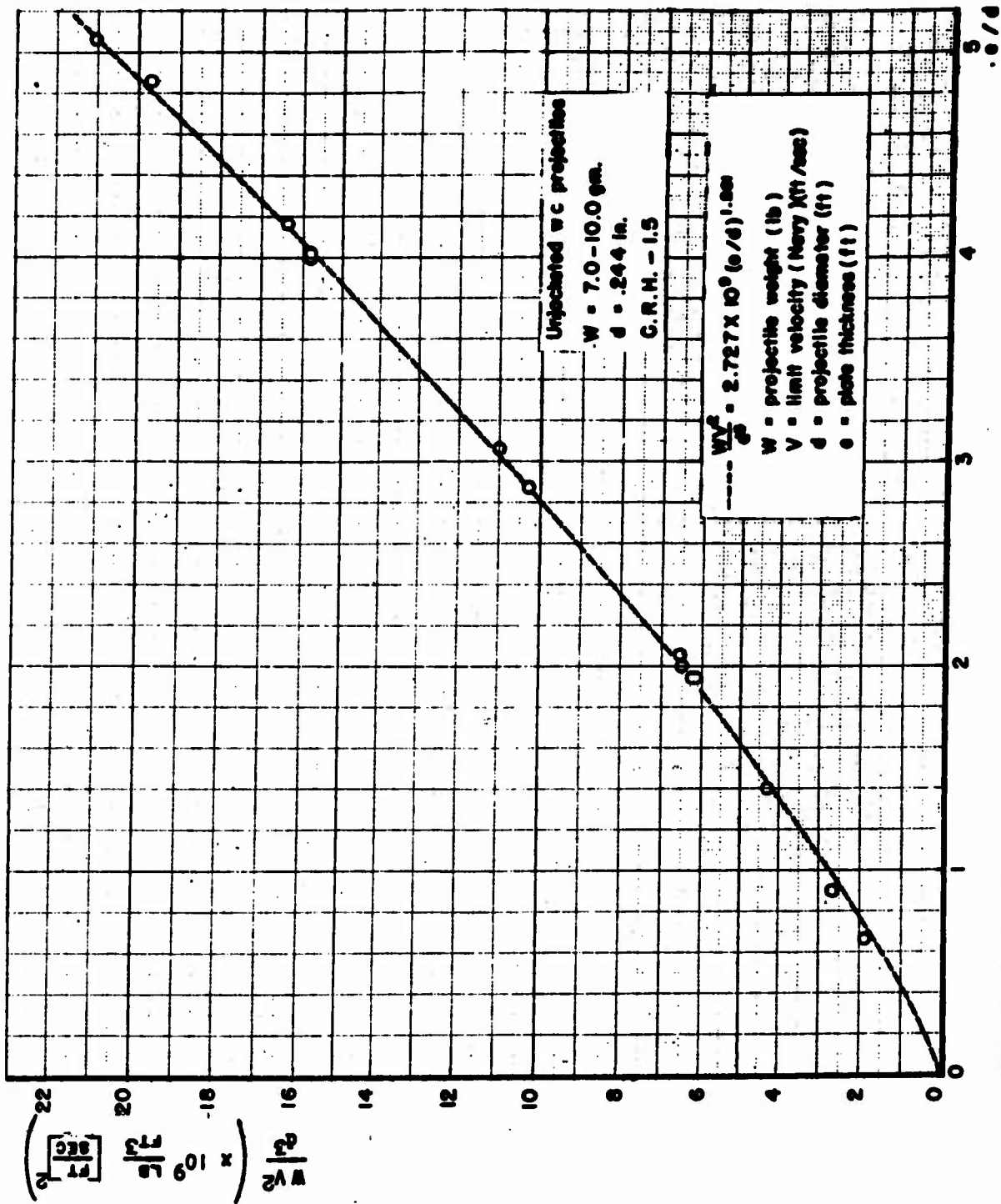


FIG. 2. SPECIFIC LIMIT ENERGY VERSUS THE RATIO OF PLATE THICKNESS t TO PROJECTILE DIAMETER d FOR UNJACKETED TUNGSTEN CARBIDE PROJECTILES TESTED AGAINST HOMOGENEOUS ARMOR (BHN 255) AT 0° OBLIQUITY.

tungsten carbide. A slight correction was made in cases of deformation of the steel,^{5/} but actual measurements are given for the tungsten carbide. It is felt that body failures had little or no effect on the limit energy; the holes were perfectly smooth and had diameters no greater than would be expected for undeformed projectiles. The reported limits for both steel and tungsten carbide should be essentially the same as for nondeforming projectiles. All perforations were of the petalling type.

To determine how the perforation limits vary with plate thickness, and with mass and nose shape of the projectile, three sets of measurements were undertaken. These are described in the following sections.

(a) Dependence of limit energy on plate thickness. -- The results of two series of perforation-limit measurements extending to high e/d values (where e is plate thickness and d is the projectile diameter) are given in the graphs of Figs. 1 and 2. Figure 1 gives limits obtained with anunjacketed caliber .30 AP M2 steel core which has an equivalent ogival radius of about 2.3 calibers.^{6/} This projectile could not be used against plate much thicker than 4 calibers because it suffered extensive deformation. Limits for plate up to 6 calibers in thickness^{7/} were obtained with tungsten carbide projectiles

^{5/} It was found that a bulge at the bourrelet always resulted in an increase in the minimum diameter of the hole and a decrease in the residual energy. For each shot where this occurred a small correction was added to the measured value for the residual energy; essentially the correction consisted of estimating the energy required to increase the size of the hole by an amount equal to the bulge of the projectile and adding this energy increment to the residual energy. After the corrections, the "best" straight line for the curve of residual energy versus striking energy was determined and this line extrapolated to give the limit energy. These corrections were necessary in only a few cases and never resulted in a change in the limit energy by over 5%.

^{6/} The nose has an actual radius of curvature of about 3.1 calibers but it is not tangent to the body at the bourrelet. Since it is not tangent the nose is not as sharp as a value of 3.1 would indicate. The equivalent value of 2.3 was chosen to make the limit-energy values consistent with those obtained in the nose-shape test. In this test only projectiles with tangent ogival heads were used.

For a picture and complete description of the caliber .30 AP M2 core see pp. 7 and 11 of the report cited in footnote 3.

^{7/} Plate having an equivalent thickness of 9 calibers has been perforated with a tungsten carbide projectile, but good limit values do not extend beyond 6 calibers.

having the same diameter as the steel cores but with a tangent ogival nose of 1.5-caliber radius. For 5.96-caliber plate the specific limit energy was

$$2.55 \times 10^{10} \frac{\text{lb}}{\text{ft}^3} \left(\frac{\text{ft}}{\text{sec}} \right)^2.$$

With the exception of this value the results for the tungsten carbide projectile appear in Fig. 2. The total thickness range covered was from $\frac{1}{4}$ to 4 calibers for the steel projectile and from $\frac{1}{2}$ to 6 calibers for the tungsten carbide.

(b) Dependence of limit energy on projectile mass. -- Use of high-density tungsten carbide and light-weight steel projectiles provides an excellent means of determining whether the limit energy depends on the mass of the projectile, or, in other words, whether the average force on the projectile is velocity dependent. The results of tests using 5.0-gm steel and 10.0-gm tungsten carbide projectiles are given in Table I for 1.0-, 2.0-, and 4.0-caliber plate. In these tests the noses of the steel projectiles were ground to have the same shape as those of tungsten carbide, and for a given thickness all shots were taken against the same plate.

Table I. Dependence of specific limit energy on projectile mass.
(homogeneous plate BHN 255, 0° obliquity)

| Ratio of Plate Thick- ness to Pro- jectile Diameter | | c/d = 1.00 | | c/d = 2.00 | | c/d = 4.00 | |
|---|--------------|---|-------------------------|---|-------------------------|---|-------------------------|
| Projectile (d = 0.244 in.) | | $\frac{WV^2}{d^3}$ | Diff. (per- cent) | $\frac{WV^2}{d^3}$ | Diff. (per- cent) | $\frac{WV^2}{d^3}$ | Diff. (per- cent) |
| Cali- ber Ogive | Mass (gm) | $\left[10^9 \frac{\text{lb}}{\text{ft}^3} \left(\frac{\text{ft}}{\text{sec}} \right)^2 \right]$ | | $\left[10^9 \frac{\text{lb}}{\text{ft}^3} \left(\frac{\text{ft}}{\text{sec}} \right)^2 \right]$ | | $\left[10^9 \frac{\text{lb}}{\text{ft}^3} \left(\frac{\text{ft}}{\text{sec}} \right)^2 \right]$ | |
| 5.0 | 10.0 | 2.80 | -5.7 | 5.87 | -0.9 | 13.9 | -0.7 |
| | 5.0 | 2.64 | | 5.82 | | 13.8 | |
| 3.0 | 10.0 | | | 5.94 | 0.0 | 14.6 | 0.7 |
| | 5.0 | 2.71 | | 5.94 | | 14.7 | |
| 1.5 | 10.0 | | -8.6 | 6.57 | -4.1 | 15.9 | |
| | 7.8 5.0 | 3.01 2.75 | | 6.30 | | shatter | |

(c) Dependence of limit energy on nose shape. -- Limit energies for 5.0-gm projectiles with tangent ogives of 5.0-, 3.0-, and 1.5-caliber radii are given in Table II. The tests were made against plates having thicknesses of 0.41, 1.0, 2.0, and 4.0 calibers; for a given thickness, all shots were taken against the same plate.

Table II. Dependence of limit energy on nose shape.
(caliber .244 projectile weighing 5.00 gm; homogeneous armor at 0° obliquity)

| Ratio of Plate Thickness to Projectile Diameter | e/d = 0.41 | | e/d = 1.00 | | e/d = 2.00 | | e/d = 4.00 | |
|---|--|-----------------|--|-----------------|--|-----------------|--|-----------------|
| Caliber Ogive | $\frac{WV^2}{d^3}$ $\left[\frac{10^9 \text{ lb (ft)}^2}{\text{ft}^3 (\text{sec})^2} \right]$ | Diff. (percent) | $\frac{WV^2}{d^3}$ $\left[\frac{10^9 \text{ lb (ft)}^2}{\text{ft}^3 (\text{sec})^2} \right]$ | Diff. (percent) | $\frac{WV^2}{d^3}$ $\left[\frac{10^9 \text{ lb (ft)}^2}{\text{ft}^3 (\text{sec})^2} \right]$ | Diff. (percent) | $\frac{WV^2}{d^3}$ $\left[\frac{10^9 \text{ lb (ft)}^2}{\text{ft}^3 (\text{sec})^2} \right]$ | Diff. (percent) |
| 5.0 | 1.01 | | 2.64 | | 5.82 | | 13.8 | |
| | | 3.0 | | 2.6 | | 2.1 | | 6.5 |
| 3.0 | 1.04 | | 2.71 | | 5.94 | | 14.7 | |
| | | 0.0 | | 4.2 | | 8.3 | | 15.2 |
| 1.5 | 1.01 | | 2.75 | | 6.30 | | 15.9* | |

*10.0-gm projectile.

3. Correlation of data

(a) Form of perforation equation and dependence of limit energy on plate thickness. -- Assuming for projectiles of a given nose shape that the thickness of plate perforated is dependent only on the striking kinetic energy of the projectile, its diameter, and "strength" of the plate material, a dimensional analysis indicates that the perforation formula must have the following form:

$$\frac{E}{d^3} = Rf(e/d)$$

or

$$\frac{WV^2}{d^3} = Rf(e/d),$$

(1)

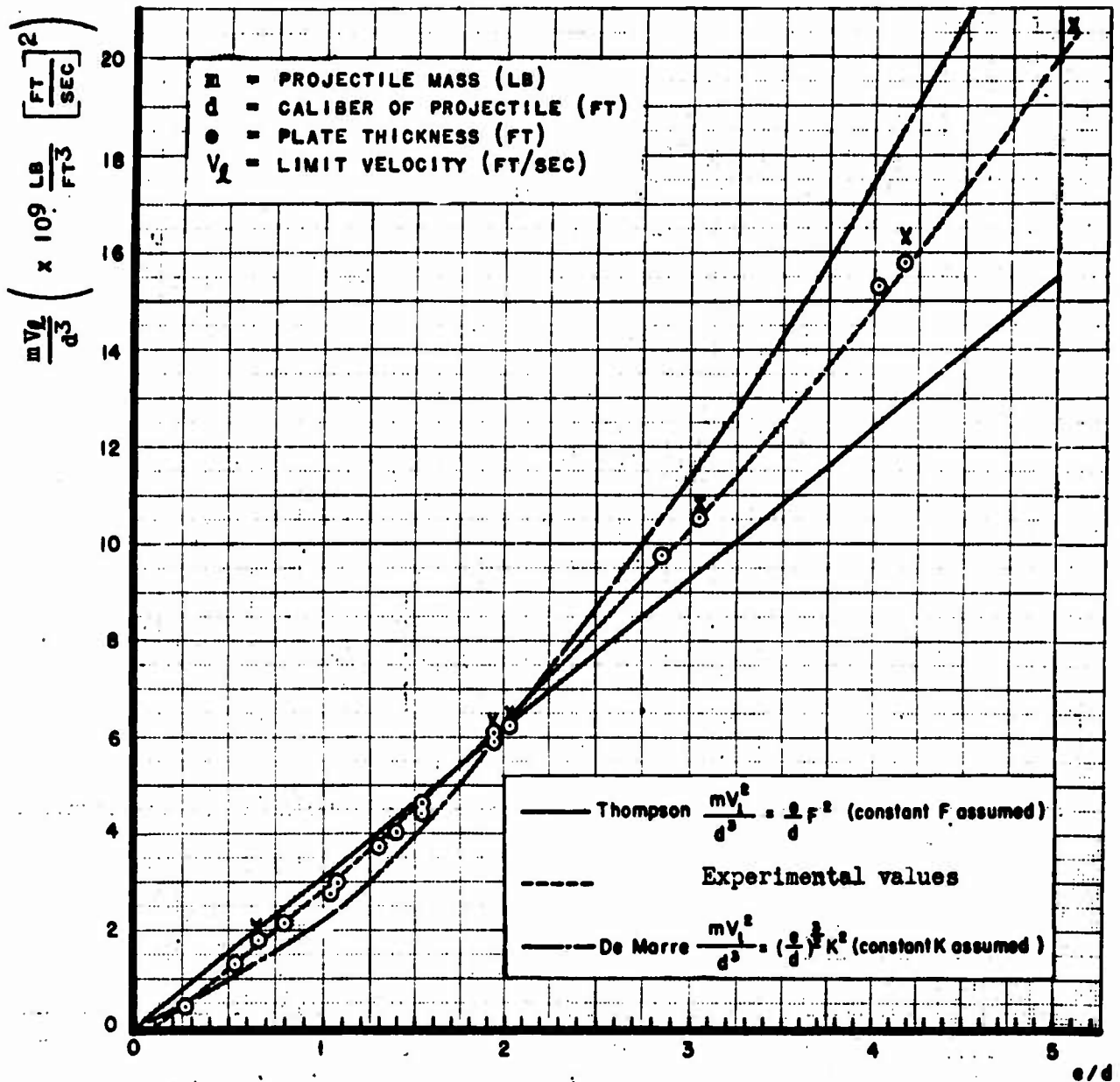


FIG. 3. SPECIFIC LIMIT ENERGY VERSUS THE RATIO OF PLATE THICKNESS TO PROJECTILE DIAMETER FOR PROJECTILES TESTED AGAINST STS ARMOR (BHN 255) AT 0° OBLIQUITY.

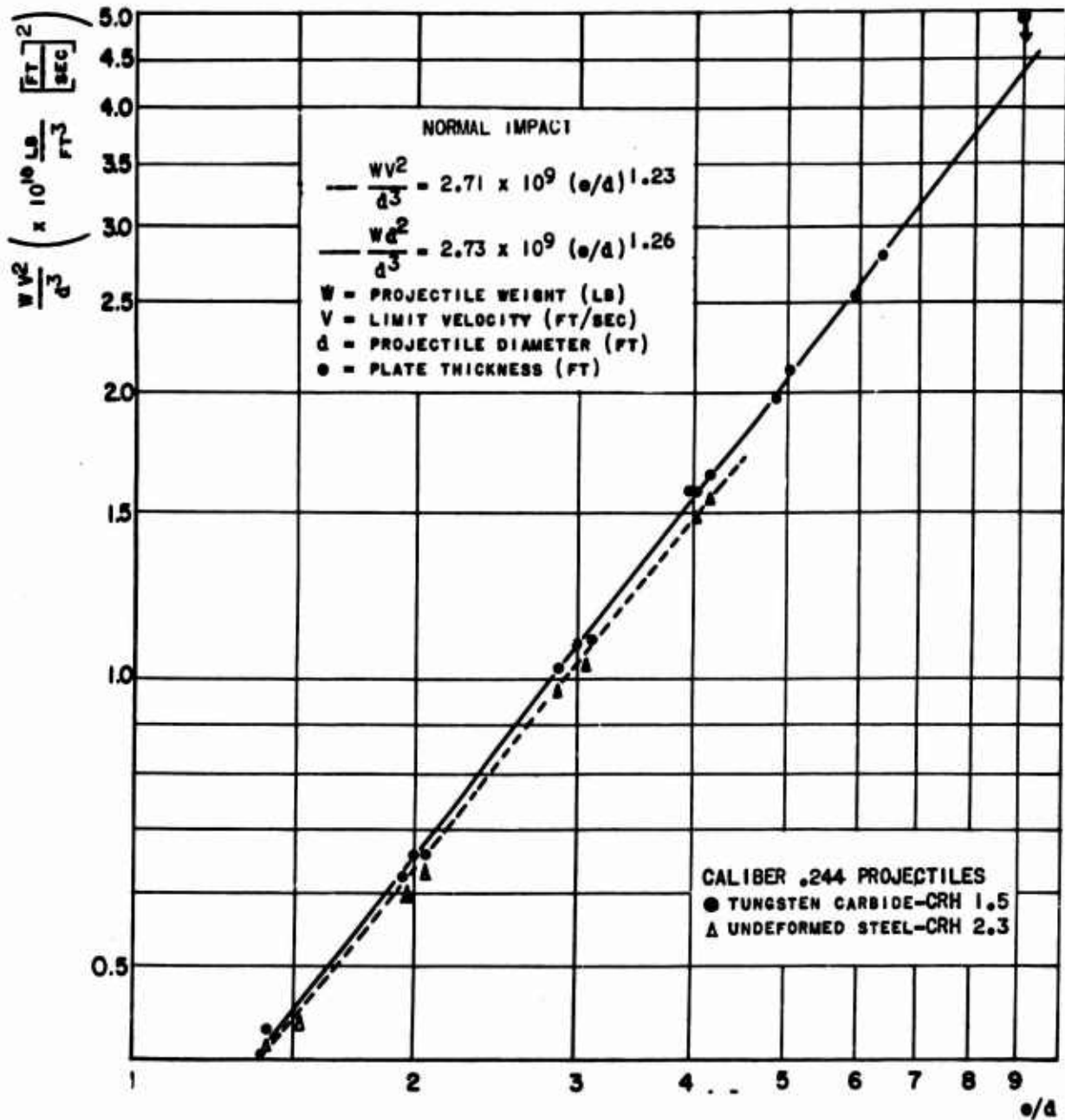


FIG. 4. LOGARITHMIC PLOT OF SPECIFIC LIMIT ENERGY VERSUS THE RATIO OF PLATE THICKNESS TO PROJECTILE DIAMETER FOR TUNGSTEN CARBIDE AND STEEL PROJECTILES TESTED AGAINST HOMOGENEOUS ARMOR (BHN 255) AT 0° OBLIQUITY.

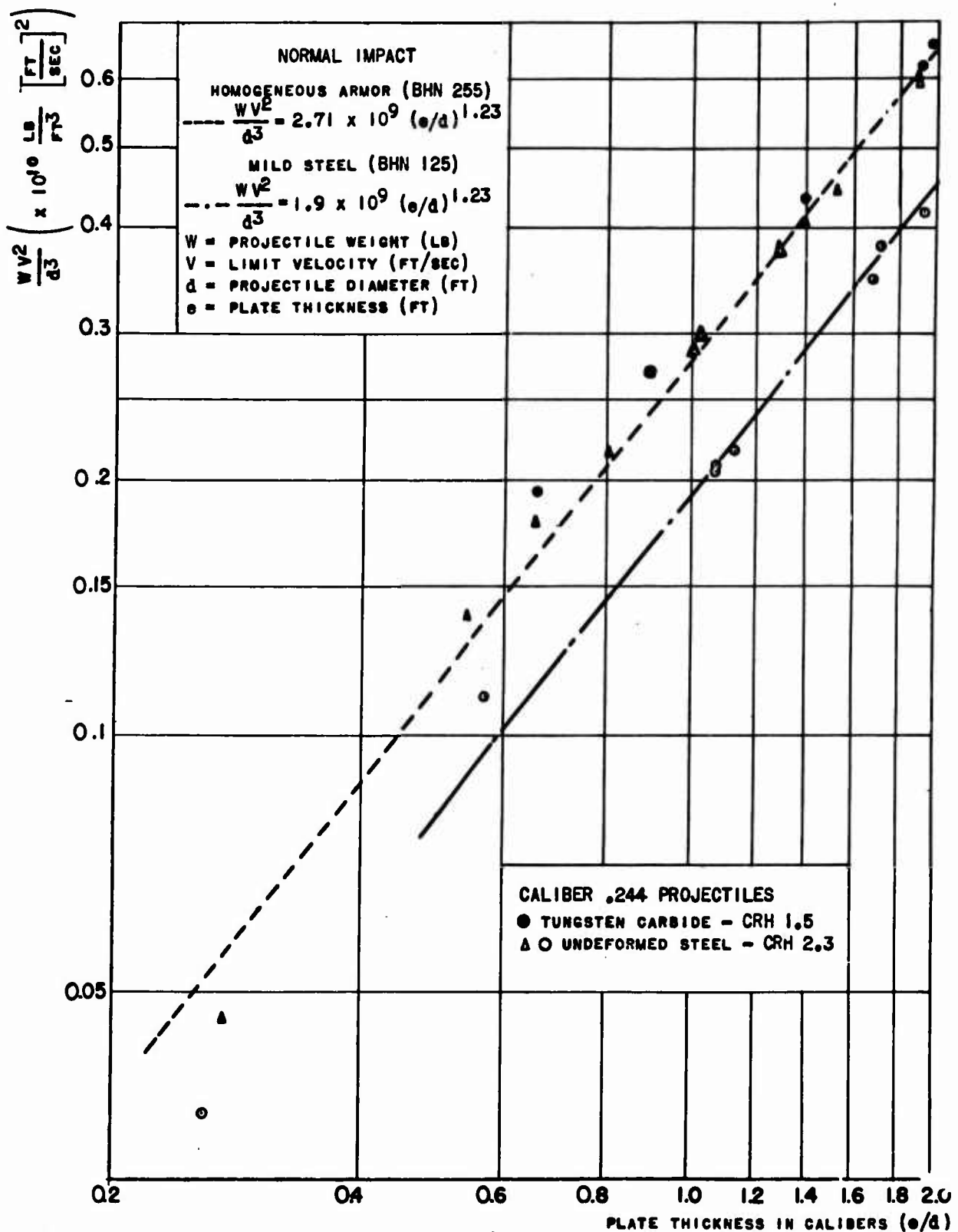


FIG. 5. LOGARITHMIC PLOT OF SPECIFIC LIMIT ENERGY VERSUS THE RATIO OF PLATE THICKNESS TO PROJECTILE DIAMETER FOR PROJECTILES FIRED AT 0° OBLIQUITY.

where $R = 2g\bar{E}$, \bar{E} is the minimum energy of the projectile required for perforation, d its maximum diameter, W its weight, and V its limit velocity. The plate thickness is represented by e , \bar{R} is a measure of the "strength" of the plate material (having units of force per unit area), and g is the acceleration due to gravity.

Choosing for $f(e/d)$ the form $(e/d)^n$, where n is arbitrary, Eq. (1) becomes

$$\frac{WV^2}{d^3} = R(e/d)^n. \quad (2)$$

The usefulness of such an expression in representing experimental data depends on the range of e/d values for which R and n can be considered constant. For extremely thin plate^{8/} n is equal to 2, while for thick plate Fig. 3 shows that n must be less than the value of 1.5 customarily used^{9/} in the De Marre formula. At best, then, there will be a region of intermediate plate thicknesses for which Eq. (2) is not highly useful.

Considering a given projectile and plates of a given hardness, the regions for which Eq. (2) is applicable can be determined from a graph of $\log WV^2/d^3$ as a function of $\log e/d$; regions of constant R and n will be represented by a straight line whose slope is equal to n . Such a graph is given in Fig. 4 for plates thicker than approximately 1.5 calibers. The data for both the steel and tungsten carbide projectiles result in straight lines with n approximately equal to 5/4. Strangely enough in the region of e/d between 0.5 and about 1.5 (see Fig. 5), the experimental points tend to fall above extrapolations of the straight lines, but for the thinnest plate ($\frac{1}{4}$ caliber) the point is below the extrapolation. That n approaches a value of 2 for very thin plate is indicated by the fact that a line drawn through the last two points has a slope of 1.54.

Thus Eq. (2) can be considered as having constant values for R and n only for plate thicker than approximately 1.5 calibers, but fortunately it is this region which is of most interest for hypervelocity projectiles. The values of

^{8/} U.S. Naval Proving Ground Report No. 1-43.

^{9/} It must also be less than 1.43 which is the value used by the British Ordnance Board.

\underline{R} (2.71×10^9 ; 2.73×10^9) and \underline{n} (1.23; 1.26) given in Fig. 4 for the steel and tungsten carbide projectiles, respectively, were obtained from the data by the method of least squares.

(b) Effect of change in projectile mass. -- One of the assumptions of the dimensional analysis used in justifying the form of Eq. (2) is that the limit energy is independent of the mass of the projectile. It appears from the results given in Table I that this assumption is reasonable for plate thicker than about 1.5 calibers, but is only approximately true for thinner plate. For example, in the case of 1.0-caliber plate a 10.0-gm projectile required 5.7 percent more energy for perforation than a similarly shaped 5.0-gm projectile, while for 2.0- and 4.0-caliber plate the differences in limit energies were negligible. The mass effect apparently decreases with increase in plate thickness.

When the mass effect is present^{10/} it is just opposite to that expected on the basis of an increase in inertial forces with increase in velocity; the projectile with the highest velocity has the lowest limit energy. It is probably significant that the effect is greatest when the plate is so thin that "dishing" is apparent, for the "dishing" decreases with increase in velocity.

(c) Effect of change in nose shape. -- As the nose of a projectile becomes more pointed the limit energy decreases. This is clear from the results in Table II. It will be noted further that the percentage difference in the limit energy produced by a given change in nose shape increases with increase in plate thickness. Since the difference is not zero for $e/d = 1$, both \underline{R} and \underline{n} must increase as the radius of curvature of the nose decreases, that is, as the nose is made blunter; this agrees with the fact that the values given at the end of Sec. 3(a) for \underline{R} and \underline{n} are both less for the steel than for the tungsten carbide projectile which has a blunter nose.

(d) Effect of changes in other parameters. -- The changes discussed in the previous sections were the only ones investigated in the present tests,

^{10/} This effect was first pointed out in the report cited in footnote 3. It is further confirmed by results against homogeneous armor 0.41 calibers thick. In this case a 7.8-gm projectile with a 1.5-caliber ogive had a limit energy 11.4 percent higher than a similarly shaped 5.0-gm projectile.

but it is well known that ballistic limits increase with increase in plate hardness up to values where brittle failures begin to occur. This increase is illustrated in Fig. 5 where limit energies of the caliber .30 AP M2 steel core are given for mild steel^{11/} (BHN 125 ± 10) as well as for homogeneous armor (BHN 255). A change in plate hardness can be taken into account, at least approximately, by altering the value of R.

It is likewise known that an increase in the diameter of a projectile usually results, for a particular value of e/d, in a decrease in the specific limit energy. For example, on comparing the caliber .244 steel core data with values obtained at the U.S. Naval Proving Ground for a 3-in. AP M79 projectile against similar plate,^{12/} it was found that for a range of plate thicknesses from 0.5 to 2.0 calibers the small-caliber results were on the average 16 percent higher.^{13/} Correlation of the two sets of measurements can be obtained by multiplying R by the scale factor

$$\left(\frac{d}{d_0}\right)^{-0.06},$$

where d_0 is the diameter of the smaller projectile.

^{11/} See report cited in footnote 3.

^{12/} See footnote 8.

^{13/} A 2 percent correction was made because of a slight difference in nose shape, but differences in caliber density have not been considered. The example is merely illustrative and is not proposed as a "scale-effect" test.

TITLE: Perforation Limits for Nonshattering Projectile Against Thick Homogeneous Armor at Normal Incidence

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ABSTRACT:

Using unjacketed caliber 0.244 projectiles that did not shatter, limit energies have been determined at normal incidence for homogeneous armor ranging in thickness from 1/4 to 6 calibers. For plates over 1.5 calibers thick, the data have been correlated by means of an empirical equation of the form $\frac{WV^2}{d^3} = R\left(\frac{e}{d}\right)^n$. W is the

weight of the projectile, V is limit velocity, R, a measure of "strength" of the plate material, e, the plate thickness, d, diameter of projectile, and n is a constant. Results show R and n are independent of the mass of the projectile only for thick plates. For projectiles of conventional nose shape n has a normal value near 1.25. There is an indication that a "scale effect" causes a small decrease in R with an increase in the caliber of the projectile, and R increases with any increase in plate hardness.

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